N89-21751

1988

NASA/ASEE SUMMER FACULTY RESEARCH FELLOWSHIP PROGRAM

MARSHALL SPACE FLIGHT CENTER
THE UNIVERSITY OF ALABAMA

# EVALUATE THE APPLICATION OF MODAL TEST AND ANALYSIS PROCESSES TO STRUCTURAL FAULT DETECTION IN MSFC - STS PROJECT ELEMENTS


Prepared By: William T. Springer

Academic Rank: Assistant Professor

University and Department: University of Arkansas
Mechanical Engineering


NASA/MSFC:

Laboratory: Test
Division: Structural Test
Branch: Dynamic Test

NASA Colleague: A. D. Coleman

Date: July 29, 1988


Contract No.: NGT 01-002-099
The University of Alabama

ABSTRACT

The Space Transportation System (STS) is a very complex and expensive flight system which is intended to carry very unique payloads into low earth orbit and return. A catastrophic failure of the STS (such as experienced in the 51-L incident) results in the loss of both human life as well as very expensive and unique hardware. One impact of this incident has been to reaffirm the need to do everything possible to insure the integrity and reliability of the STS is sufficient to produce a safe flight.

One means of achieving this goal is to expand the number of inspection technologies available for use on the STS. The purpose of the activity reported here was to begin to evaluate the possible use of assessing the structural integrity of STS components for which Marshall Space Flight Center (MSFC) has responsibility. This entailed reviewing the available literature and determining a low-level experimental program which could be carried out by MSFC and would help establish the feasibility of using this technology for structural fault detection.

## ACKNOWLEDGEMENTS

The author wishes to express his appreciation to the NASA/ASEE Summer Faculty Fellowship Program for the opportunity to participate in this program. In addition, he would like to specifically thank Michael Freeman, Ernestine Cothran, and Billie Swinford for the support and guidance they provided this summer.

To NASA Colleagues A. D. Coleman and C. A. Kirby (Chief) of the Dynamics TEst Branch, and G. B. Waggoner, Chief of the Structural Test Division, the author wishes to extend his gratitude for their interest and encouragement.

Finally, to G. D. Johnston (former Chief, Dynamics Test Branch) of Vibration and Acoustics, Inc., thanks are due for his support and assistance, both past and present.

# INTRODUCTION

During recent years it has become increasingly necessary to assess the integrity of existing structural systems so as to determine thier suitability for continued use. Examples of these structural systems include commerical and military aircraft, offshore oil platforms, commerical buildings in earthquake prone regions, and bridges. All of these examples are structures which represent a significant initial capital investment and/or the potential for harm to either human occupants or the environment or both if they fail.

Recently, the Space Transportation System (STS) has been added to this list. The STS has many components which are reusable, and the Orbiter Vehicle is the most recognizable of these. In addition to the usual problems encountered in inspecting and evaluating the condition of a typical aerospace structure, the STS has several unique requirements which must be accomadated. These include exposure to an extremely hostile and wide ranging environment, the need to significantly reconfigure the vehicle for each flight, and a very tight schedule of access to the vehicle between flights.

The technology currently used to assess the integrity of the orbiter and other pieces of flight structure requires direct access to the areas to be inspected. Additionally, these technologies (such as ultrasonics, acoustic emissions, dye penetrants, and others) require the surface of the component to be inspected to be clean, and in many instances, the component must be physically removed from the structure. The result is an extremely localized inspection program which requires the expenditure of large amounts of time and labor, and can result in a degredation of the structural integrity just do to the disassembly-reassembly cycle involved. The DC-10 crash on take-off in Chicago a few years ago is a dramatic example of this possibility.

Less tragic but equally costly results can be produced by simple mistakes such as a bearing being improperly installed after an inspection of a large piece of equipment in the petrochemical or power generation industry. Therefore, any inspection scheme which either eliminates the need for or reduces the frequency of this type of detailed inspection process without sacrificing the quality of the inspection can provide significant savings to the industry using it.

This approach has been used successfully in many process related industries and is refered to as "preventive maintenance". By monitoring such things as machine vibrations and the chemical composition of lubricants on a regular basis, it is possible to keep a running log of the condition of important pieces of equipment without removing them from service. In this manner, down-time and equipment outages can be controlled and scheduled to coincide with other related activities.

The purpose of the work performed under this program was to begin the evaluation of modal analysis methods for use as a structural fault detection tool. The major advantages this method has over those currently in use are that it is a global inspection technique, and does not require disassembly of the structure to be inspected. It may also be possible to extend the application of this technology to a point where it can function in a preventive maintenance role. However, the current interest in this technology centers around its global measurement capability, and the fact that it can be utilized without requiring any disassembly of the structure.

## PROJECT DESCRIPTION

As mentioned earlier, modal analysis and testing techniques have tow major benefits to offer as a Non-Destructive Evaluation (NDE) method. These are 1) the global nature of the evaluation and 2) the fact that the evaluation can be performed without disassembling the structure. However, there are some significant questions which must be investigated before it will be possible to determine the extent of the usefulness of this method as an NDE tool.

These concern themselves with such things as the type of fixturing, if any, required, the amount and type of data to be taken, the accuracy and repeatability required for the data, the type of data processing to be used, the manner in which the data should be presented, the rationale for interpreting the data, and so forth. While this list is far from complete, it serves to illustrate the complexity of this issue.

Therefore, it was decided that the best approach to take in the present effort was to review the literature available on this topic, and then begin a low-level test program that could be carried out by the Dynamic Test Branch at MFSC. This test program would serve to familiarize their personnel with the use of modal test methods for NDE purposes, illustrate the impact of accuracy and repeatability on the test data, allow some preliminary evaluation of various data processing and presentation methods, and to generally illustrate how typical aerospace structural systems will behave when damage is present. The results of these preliminary investigations will provide the basic information required to determine how best to proceed with a more advanced and ambitious evaluation program.

### Literature Survey

The fact that the frequency content of a vibrating system changes as the physical characteristics of the sytem change has been used to advantage in several areas. These range from the above mentioned application to preventive maintenance and troubleshooting as described by Downham and Woods [5], Glew and Watson [6], Cempel [82], and Mutch and Russell [86] to the determination of the elastic properties of structural adhesives as explained by Adams and Coppendale [81].

One does not have to expend much effort to discover that this concept has been applied in many different forms to many different problems. This is demonstrated by the set of references listed at the end of this report. While this listis by no means complete, it does serve to illustrate the point quite well. In particular, these articles can be divided into several general catagories, and they will be described in this manner.

Two areas which have received considerable attention in recent years are civil engineering structures and offshore oil platforms. Yao and his colleagues [11,15,16,78-80] have published extensively on the subject of inspecting civil engineering structures. The goal being to define a method of assessing the integrity of these structures after their exposure to some situation such as an earthquake which could severly damage a structure without causing it to collapse. The outcome of this work has been a probabilistic method to quantify the damage as either minor or moderate or severe coupled with an attempt to computerize the evaluation process. Inputs range from subjective evaluations made by inspectors to actual empirical data. There is no indication of how successfully the system works.

Krauthammer [9] has suggested a numerical evaluation plan similar in intent to that of Yao. Matzen and Hardee [10] have demonstrated a numerical method based on the Hessian matrix for determining if an element in an FEM model has a value of stiffness equal to zero. The ability of the method to determine a value other than zero was not studied. Sparks, Jeary and de Souza [17] are but one set of investigators that have examined the use of ambient excitation to determine the dynamic properties of a building. Kopff [21] has attempted to set down a rationale for inspecting large natural convection cooling towers also using ambient excitation. All of these investigations are lacking both experimental verification and a method of correlating the presence of damage to changes in dynamic properties.

Another type of structure which has received a fair amount of attention is the offshore oil platform. This class of structure is both unique and extremely expensive. Also, a sudden failure of such a structure can have a tremendous impact on the environment as well as the potential loss of human life. The two main obstacles faced by investigators in this area are both related to economics. The first is the general need to find an answer quickly when structural damage is suspected coupled with the lack of interest on the part of the petroleum industry in supporting fundamental research on this topic. The second is the fact that the platform cannot be casually taken out of service at any time during its life. The cost of putting these sturctures into service and then keeping them operating is enormous. Therefore, any NDE which must be performed on these structures must take place while the platform is operating. This can complicate the measurement and analysis process to the point where it is virtually fruitless.

Loland, Mackenzie, Begg and Bendat [8,14,19] have highlighted some of these difficulties. One of the most significant of these is determining an adequate model of the platform which can be used with modal analysis procedures to determine structural integrity. This is not a simple problem. Kummer, Yang and Dagalakis [13] have applied the "log decrement" technique to simple structures to detect the presence of fatigue cracks with an eye to applying the results to offshore platforms. This application to real structures has yet to be accomplished. Vanduerzen, Leuridan and Doucet [28] have also applied modal analysis techniques to an offshore platform. Again, the model of the platform used was extremely simple and made it difficult to determine the precise condition of the structure.

Large rotating equipment has also received attention. The concern is these papers is the ability to avoid an unexpected catastrophic failure of these extremely large and expensive pieces of equipment. In addition, if the need to disassemble this equipment unnecessarily can be avoided, the financial benefits to the owner are significant. This concern results from the fact that the materials used in these large pieces of equipment are not, typically, very damage tolerant. Therefore, a relatively small crack can be devistating. References 59 to 63 and 67 describe several different variations of this problem. In all cases, no clear choice for an obvious monitoring scheme is identified.

There has also been much written in way of what can be termed general application of vibration analysis to damage detection or the detection of structural changes. The amount of published literature is extensive and References 20, 22, 23, 25-27, 29, 30, 43-58, 64-72, 84, 85 and 88 constitute a small but representative sample of the work in this area. Virtually all of this work concentrates on examining very simple structures or structural elements and, again, it is unclear whether this information can be applied to real structural systems.

There have also been a number of theses and dissertations written on this general subject, and References 31 to 41 are reflective of this work. Of this body of work, only the contributions of Haisty [40] and Duerr [41] have addressed the need of providing the analyst as well as the experimentalist with the capability of evaluating the effect damage will have on the dynamic properties of a structure. In the long term, this will be an important feature of this technology. Again, none of this work has been applied to large structural systems.

One method which seems to be finding some favor is to force an FEM model to exhibit the measured structural vibration characteristics. Typically, this approach uses some type of optimization routine to determine the final configuration. Most of the work which falls into this category is either proprietary or else just developing. More of this work should be coming to publication in the near future.

## Present Investigation

The need to monitor the structural integrity of aerospace structures is well established. The number of these systems in commerical service alone is staggering. Recent estimates put the number of departures and arrivals in excess of 26,000 per day. Each of these flights carries a large number of passengers and operates, at least a portion of the time, in areas of high population density. These facts all combine to produce a situation that would result in the loss of a large number of human lives if a catastrophic structural failure should occur.

In addition to this pressure, the military also has a tremendous inventory of aircraft of all types. While, in general, these aircraft carry fewer passengers and crew than those in civilian service, the shear number of aircraft in the military inventory establishes an economic imperative, if nothing else, to keep them in the best possible health. However, it is not at all clear how the needed inspections should be accomplished. This situation is well documented by Sproat and Rowe [87]. They point out how the existence of all the competing inspection technologies complicate the issue even more. This reference details a four year test program carried out by Lockheed-Georgia for the Air Force which was intended to evaluate all of these competing methods. But, as stated earlier, everyone agrees that inspections are needed.

One approach to this problem has been to measure the strain experienced by the structural component or assembly of interest and use this data to make a determination of its integrity. An early attempt to implement this strategy is documented by Bochniak and Garcia [42]. This report describes a tweleve channel strain measurement and recording system which was developed for the Navy, and intended for use as an aircraft structural integrity monitoring device. There is no information concerning the success of the monitoring program.

A more recent attempt to accomplish the same goal is presented by Bruinsma et al. [3], and details the use of fiber-optic strain measurements to provide information concerning the structural integrity of composite materials. Again, this reference describes only the data acquisition strategy and no information is presented concerning an actual application of this device in a real system.

The investigation presented here resulted, in part, from the interest generated by a Level II Change Request and PRCBD #S40155 titled "Orbiter Structural Inspection Via Modal Processes." This request was initiated by Mr. Walter M. West Jr., JSC-ES4, as a possible solution to the problem of inspecting components of the shuttle which cannot practically be inspected using other technologies. The particular items of concern are control surfaces. These components are typically built-up structures and can sustain internal damage which cannot be detected by conventional NDE methods without removal of the component's aluminum skin.

The prime motivation for this concern resulted from an acoustic test of the body flap of the Space Shuttle. Cheng, Dunham and Joanides [83] have documented the basic test procedure and expected test results. After the completion of this evaluation program on the body flap, a modal survey revealed that some of its dynamic characteristics had changed. West determined that damage had accumulated in the body flap by reviewing the vibraitonal mode shapes.

Later, West [74-76] developed a technique for locating damage in structures using a modal vector correlation coefficient. The structure is partitioned into several components and the correlation coefficient between baseline and post-service mode shapes are calculated. For components in which no change has occured, the correlation coefficient is near unity, while in damaged segments the value of the correlation coefficient is less than one. The procedure was applied to Space Shuttle test specimens with success.

Haisty, West and Mitchell [77] applied West's technique to the Space Shuttle Orbiter body flap test specimen with good results. Several damage sites were correctly identified using this technique which were not detected by conventional

NDE techniques. While this technique can locate damage in structures reasonably well, it is unable to determine the extent fo the damage.

As an extension of these activities, work has recently completed at JSC which applied this technique to a small Cessna airframe. The goal was to inspect the control surfaces while they are installed in the airplane. The initial damage placed in the structure was used to evaluate the concept of using local modes (i.e. modes primarily attributed to the subsystem only) to detect damage in the control surfaces. This work has produced results which were very favorable and has lead to the inclusion of this approach in the inspection program for the Orbiter.

Further support for the use of modal analysis procedures as an NDE tool has been provided by the Structural Dynamics Research Corporation [73]. SDRC has reported cases in which damage in spacecraft and airplanes has been diagnosed as the result of routine modal tests. They conclude that modal analysis can be readily adapted to the identification of structural failures, that frequency response functions can quickly give an indication of whether or not damage has occurred in the structure, and the mode shapes can provide information about where the structural problem has occurred. This work also stops short of quantifying the damage present.

The preliminary results obtained in the experimentation begun this summer at MSFC-ET53 demonstrates that the success achieved at JSC may not translate directly to all structures. The boxbeam structure tested in this program was damaged in both primary and secondary structural members and the MAC values calculated in the same manner as was done at JSC. The results indicate that for this structure at least the damage does not become apparent in the MAC values until rather large cuts have been made. Also, the modes which intuitively seem like they would be the most effected are not the modes which exhibit the greatest variation in MAC values. This gives further credence to the need for more work in this area so that a logical strategy for applying this technology can be formulated.

In addition to the work completed at JSC and the interest in evaluating this technology for use by MSFC-ET53, there are additional groups within NASA with similar problems. The first of these is MSFC-PD22. This group is working on development programs utilizing new materials which will have very unique properties. Because of this, it will be extremely important to have reliable, efficient, and economic NDE methods available for use on these systems. The propulsion group at MSFC also has interest in using measured quanities to determine the condition of the SSME and other related hardware. Many of the problems associated with these activities are similar, at least in form, to those reviewed in this report. Last, there is an apparent interest at the Langley Research Center in evaluating the application of modal analysis methods to the problem of assessing acoustic fatigue damage.

## Existing Problems

The following problems currently exist and must be solved in order to make modal analysis an effective and useful NDE method:

1. Measurement noise.

2. Available excitation techniques for certain situations may limit the usefulness of the data.

3. Beat methods for data presentation and processing are unclear.

4. Measurement accuracy and repeatability requirements are unknown.

5. Interpretation of data to yield damage level and/or location values not yet clearly possible in real structures.

6. Quantity of data required to make an accurate damage assessment is unknown.

7. Low cost transducer development is needed.

8. Very little understanding of damage/structure interaction.

9. Much information on this general topic is available in the literature but its usefulness is not clear.

10. Expense of hardware and software required for data acquisition and analysis is still high.

11. Desire to apply this technology to NDE of new materials before simple structures are understood.

12. Uniqueness of the predicted damage location and/or level values may be questionable.

13. Fixturing needed to insure reproduceable test conditions is unclear and maybe extensive.

The problem of measurement noise is being addressed by Wicks and Mitchell [1,2,24], and their work seems to be bringing this problem under control. Concern over the available excitation methods is of less importance in the aerospace industry than in the other application areas mentioned earlier because of the control one has over the test article during the inspection process.

In the future, on the other hand, if this method is to be expanded to include in-service responses in the evaluation process as well, the information contained in these measurements will have to be examined very closely to insure that it will produce useful estimates of the integrity ofthe structure. It is possible that the measurement sites selected for use in the modal test which would be done when the system is out of service may not provide the best possible information from the in-service measurements.

Another issue is the number of in-service measurement sites needed. This number will have a significant impact on not only the quality of the data but on the cost of the monitoring system as well. Therefore, it will be very important to select the measurement sites with great care and deliberation.

The need to develop low cost transducers stems from the desire to eventually be able to install the required instrumentation in the vehicle as a part of the construction process. In this way considerable effort and expense can be avoided during the service life of the vehicle by eliminating the need to install and remove large numbers of transducers each time a structural integrity assessment was to be made. At the same time, adequate instrumentation would still be available to permit a complete inspection to be prformed.

Obviously, how this technology is applied by the general public and the cost of the data acquisition and analysis equipment are items which cannot be controlled. However, these are two issues which will play a significant role in the development and utility of this technology for NDE purposes.

The remainder of the items listed above will have to be addressed through comprehensive research efforts.

## CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

The ability of modal analysis methods to provide information which can be used for the NDE of structural systems is clear. However, many issues concerning the efficient and accurate utilization of this data for NDE purposes are unresolved. These include, but are not limited to, the amount of data needed, how accurate and repeatable the data must be, how this data should be processed and presented, and how the damage interacts with the dynamic characteristics of the structure. A comprehensive research effort will be required to successfully address these concerns.

### Recommendations

The preliminary results obtained this summer indicate both the promise and pitfalls to be encountered in using modal analysis methods for NDE of structural systems. Based on these results, the recommendations listed below will provide needed insight into the problem areas delineated earlier.

1. Begin a research effort which will determine which of the various dynamic characteristics should be monitored, provide guidance on how to monitor them, and give an indication of the measurement accuracy needed when they are monitored.

2. Begin a research effort to determine if it will be possible to characterize as well as locate the structural faults of interest in a particular structure.

3. Investigate how to incorporate this ability into the structural design/analysis cycle so that future designs can be improved.

4. Begin a basic research effort to characterize the dynamic behavior of fundamental composite structural elements in the same fashion as has been done for metallic structures.

## BIBLIOGRAPHY


1. Wicks, A. L. and Mitchell, L. D., "A New Means of Estimation of Frequency Response Functions in the Presence of Uncorrelated Signals, Part I," Proceedings of the Spring Meeting of the Society for Experimental Mechanics, 1987, pp. 629-634.

2. Wicks, A. L., "Frequency Response Function Estimation and Quality Statistic," Proceedings of the Spring Meeting of the Society for Experimental Mechanics, 1987, pp. 517-523.

3. Bruinsma, A. J. A., et al., "Fibre-Optic Strain Measurement for Structural Integrity Monitoring," Proceedings of the Second International Conference on Optical Sensors, 1984, pp. 399-402.

4. Rakshin, A. F. and Sidorov, O. T., "Determination of the Degree of Defectiveness in Structural Components," Soviet Journal of Nondestructive Testing, Vol. 18, No. 3, November 1982, pp. 158-161 (Translation).

5. Downham, E. and Woods, R., "The Rationale of Montioring Vibration on Rotating Machinery in Continuously Operating Process Plant," ASME Paper No. 71-Vibr-96, 1971.

6. Glew, C. A. W. and Watson, D., "Vibration Analysis as a Maintenance Tool," Transactions of the Institute of Marine Engineers, Canadian Division, Supp. No. 32, June 1968, pp. 18-29.

7. Petroski, H. J. and Glazik, J. L., Jr., "The Response of Cracked Cylindrical Shells," Journal of Applied Mechanics, Trans. ASME, Vol. 47, June 1980, pp. 444-446.

8. Loland, O. and Mackenzie, A. C., "On the Natural Frequencies of Damaged Offshore Oil Platforms," Mech. Res. Comm., Vol. 1, 1974, pp. 353-354.

9. Krauthammer, T., "A 'Numerical Gauge' for Structural Assessment," Shock and Vibration Bulletin, No. 56, Part 1, 1986, pp. 179-194.

10. Matzen, Vernon Charles and Hardee, Joseph Earlton, Jr., "Mathematical Modelling of Indeterminate Trusses," Proceedings of the Second Specialty Conference on Dynamic

Response of Structures, 1981, pp. 687-697.

11. Yao, J. T. P., "Damage Detection Using System Identification," Proceedings of the Spring Meeting of the Society for Experimental Mechanics, 1987, pp. 383-384.

12. Liu, Dahsin, Sun, C. T. and Malvern, L. E., "Structural Degradation of Impacted Graphite/Epoxy Laminates," Shock and Vibration Bulletin, No. 56, Part 2, 1986, pp. 51-60.

13. Kummer, E., Yang, J. C. S. and Dagalakis, N., "Detection of Fatigue Cracks in Structural Members," Proceedings of the Second Speciality Conference on Dynamic Response of Structures, 1981, pp. 445-461.

14. Loland, O., Mackenzie, A. C. and Begg, R. D., "Integrity Monitoring of Fixed, Steel Offshore Oil Platforms," BSSM/RINA Joint Conference of Measruement in the Offshore Industry, 1975.

15. Liu, Shih-Chi and Yao, James T. P., "Structural Identification Concept," Journal Of The Structural Division, ASCE, Vol. 104, ST12, December 1978, pp. 1845-1858.

16. Yao, James T. P., "Dammage Assessment of Existing Structures," Journal Of The Engineering Mechanics Division, ASCE, Vol. 106, No. EM4, August 1980, pp. 785-799.

17. Sparks, P. R., Jeary, A. P. and de Souza, V. C. M., "A Study of the Use of Ambient Vibration Measurements to Detect Changes in the Structural Characteristics of a Building," Proceedings of the Second Speciality Conference on Dynamic Response of Structures, 1981, pp. 189-200.

18. Cole, Henry A., Jr., "On-Line Failure Detection and Damping Measurements of Areospace Structures by Random Decrement Signatures," NASA CR-2205, 1973, 75 pages.

19. Begg, R. D. and Bendat, J. S., "Instrumentation and Analysis Techniques for the Monitoring of Offshore Structures," Petroleum Times, October 1, 1976, pp. 29 and 35.

20. Wang, J. T. S., Liu, Y. Y. and Gibby, J. A., "Vibrations of Split Beams," Journal of Sound and Vibration, Vol. 84, No. 4, 1982, pp. 491-502.

21. Kopff, Paul, "Experimental Modal Analysis for Structural Damage Assessment: The Case of Natural Convection Cooling Towers," Proceedings of the Fifth International Modal

Analysis Conference, 1987, pp. 122-126.

22. Lai, Hsin-Yi, "Computer Aided Fault Diagnosis of Crank Systems Using Engine Vibration Data," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 248-253.

23. Brown, T. A., "The Identification of Spatial Parameter Changes Via Modal Analysis," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 267-273.

24. Mitchell, L. D., et al., "An Unbiased Frequency Response Fuction Estimator," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 364-373.

25. Hopton, Gregory W. and Deblauwe, Filip, "Relationships Between Analysis Errors and Complex Mode Shapes," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 381-388.

26. Afolabi, D., "An Anti-Resonance Technique for Detecting Structural Damage," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 491-495.

27. Wang, Weiji and Zhang, Azhou, "Sensitivity Analysis in Fault Vibration Diagnosis of Structures," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 496-501.

28. Vandeurzen, U., Leuridan, J. and Doucet, Y., "Structure Monitoring Using a Diagnosis Technique Based on Combined Use of FEA and Test," Proceedings of the Fifth International Modal Analysis Conference, 1987, pp. 1338-1346.

29. Springer, W. T., Lawrence, K. L. and Lawley, T. J., "The Effect of a Symmetric Discontinuity on Adjacent Material in a Longitudinally Vibrating Uniform Beam," Experimental Mechanics, SEM, To appear.

30. Springer, W. T., Lawrence, K. L. and Lawley, T. J., "Damage Assessment Based on the Structural Frequency Response Function," Experimental Mechanics, SEM, To appear.

31. Bourne, C. A., Material Damping As A Means Of Quantifying Fatigue Damage, Masters Thesis, Air Force Institute of Technology, 1978.

32. Chen, S. H., System Identification And Damage Assessment Of Existing Structures, Ph.D. Dissertation,

Purdue University, 1980.

33. Toussi, S., System Identification Methods For The Evaluation Of Structural Damage, Ph.D. Dissertation, Purdue University, 1982.

34. Stephens, J. E., Structural Damage Assessment Using Response Measurements, Ph.D. Dissertation, Purdue University, 1985.

35. Tsai, Wen-Hu, Detecting And Locating Damages In Complex Structures By The System Identification Technique, Ph.D. Dissertation, University of Maryland, 1985.

36. Springer, W. T., The Vibrational Characteristics of Uniform Bars Containing a Symmetric Discontinuity in Stiffness Applied to Structural Integrity Monitoring, Ph.D. Dissertation, University of Texas at Arlington, 1982.

37. Reznicek, M. E., The Transverse Vibrational Characteristics of Symmetrically Damaged Bars, Masters Thesis, University of Arkansas, 1984.

38. Haisty, B. S., Damage Assessment Using the Longitudinal Vibrational Characteristics of Uniform Bars, Masters Thesis, University of Arkansas, 1984.

39. Moshrefi, N., The Transverse Vibrational Behavior of a Peripherally Cracked Pipe and a Uniformly Corroded Pipe, Masters Thesis, University of Arkansas, 1985.

40. Haisty, B. S., Development and Application of a Cracked-Beam Finite Element and a Cracked-Beam Modal Element for Assessing the Effects of Damage on the Modal Properties of Mechanical Systems, Ph.D. Dissertation, University of Arkansas, 1986.

41. Duerr, R. R., Development and Evaluation of a Dynamic Transfer Matrix for a Damaged Uniform Beam, Masters Thesis, University of Arkansas, 1987.

42. Bochniak, J. and Garcia, R., Structural Integrity Monitoring System, Report No. NADC-77101-30, 1979, 82 pages.

43. Hetenyi, M., "Deflection of Beams of Varying Cross Section," Trans. ASME, Vol. 59, March 1937, pp. A-49-A-52.

44. Kirmser, P. G., "The Effect of Discontinuities on the Natural Frequencies of Beams," Proceedings of the ASTM, Vol. 44, pp. 897-904.

45. Thomson, W. T., "Vibration of Slender Bars With Discontinuities in Stiffness," Journal of Applied Mechanics, Trans. ASME, Vol. 6, June 1949, pp. 203-207.

46. Adams, R. D., et al., "A Vibration Technique for Non-Destructively Assessing the Integrity of Structures," Journal of Mechanical Engineeering Science, Vol. 20, No. 2, 1978, pp. 93-100.

47. Cawley, P. and Adams, R. D., "The Location of Defects in Structures From Measurements of Natural Frequencies," Journal of Strain Analysis," Vol. 14, No. 2, 1979, pp.49-57.

48. Cawley, P. and Adams, R. D., "Defect Location in Structures by a Vibration Technique," ASME Paper No. 79-DET-46, 1979.

49. Ju, F. D., et al., Diagnosis of Fracture Damage in Simple Structures, Bureau of Engineering Research, Report No. CE-62(82) AFOSR-993-1, October 1982.

50. Ju, F. D., Wong, E. T. and Lopez, T. L., "Modal Method in Diagnosis of Fracture Damage in Simple Structures," Productive Applications of Mechanical Vibrations, Applied Mechanics Division, Vol. 52, ASME, 1982, pp. 113-125.

51. Gudmundson, P., "Eigenfrequency Changes of Structures Due to Cracks, Nothches or Other Geometrical Changes," Journal of Mech. Phys. Solids, Vol. 30, NO. 5, 1982, pp. 339-353.

52. Gudmundson, P., "Changes in Modal Parameters Resulting From Small Cracks," Proceedings of the Second International Modal Analysisi Conference, 1984, pp. 690-697.

53. Gudmundson, P., "The Dynamic Behavior of Slender Structures With Cross-Sectional Cracks," Journal of Mech. Phys. Solids, 1983.

54. Reznicek, M. E. and Springer, W. T., "Damage Assessment of Transversely Vibrating Uniform Beams Containing a Symmetric Discontinuity," Proceedings of the Spring Meeting of the Society for Experimental Mechanics, 1985, pp. 404-409.

55. Haisty, B. S. and Springer, W. T., "Identification of Multiple Discontinuities in a Uniform Beam Using Longitudinal Vibration Properties," Proceedings of the 40th Mechanical Failures Prevention Group, National Bureau of Standards, 1985.

56. Haisty, B. S. and Springer, W. T., "The Longitudinal Vibration Characteristics of a Uniform Bar Containing Two Symmetric Discontinuities," Proceedings of the Spring Meeting of the Society for Experimental Mechanics, 1985, pp. 389-393.

57. Moshrefi, N., Sreshta, H. A. and Springer, W. T., "The Transverse Vibration Characteristics of an Externally Damaged Pipe," Vibration Analysis to Improve Reliability and Reduce Failure, Applied Mechanics Division, Vol. , ASME, 1985, pp. 23-30.

58. Al-Ansary, M. D. and Azagem, K. M., "A Modal Model for Fatigue Crack Non-Destructive Testing," Proceedings of the Fourth International Modal Analysis Conference, 1986, pp. 202-208.

59. Henry, T. A. and Okah-Avae, B. E., "Vibrations in Cracked Shafts," Proceedings of the First International Conference of Vibrations in Rotating Machinery, I. Mech. E., Vol. 9, No. C162/76, 1976, pp. 15-19.

60. Mayes, J. W. and Davies, W. G. R., "The Vibrational Behaviour of a Rotating Shaft System Containing a Transverse Crack," Proceedings of the First International Conference of Vibrations in Rotating Machinery, I. Mech. E., Vol. 9, No. C168/76, 1976, pp. 53-64.

61. Gasch, R., "Dynamic Behavior of a Simple Rotor With a Cross-Sectional Crack," Proceedings of the First International Conference of Vibrations in Rotating Machinery, I. Mech. E., Vol. 9, No. C178/76, 1976, pp. 123-128.

62. Grabowski, B., "Vibrational Behavior of a Turbine Rotor Containing a Transverse Crack," Journal of Mechanical Design, Trans. ASME, Vol. 102, No. 1, January 1980, pp. 140-146.

63. Rauch, A., "Shaft Cracking Supervision of Heavy Turbine Rotors by FEM Method," Proceedings of the Third International Modal Analysis Conference, 1985, pp. 714-722.

64. Chondros, T. G. and Dimarogonas, A. D., "Identification of Cracks in Circular Plates Welded at the Contour," ASME Paper No. 79-DET-106, 1979.

65. Chondros, T. G. and Dimarogonas, A. D., "Identification of Cracks in Welded Joints of Complex Structures," Journal of Sound and Vibration, Vol. 69, No. 4, 1980, pp. 531-538.

66. Anifantis, N. and Dimarogonas, A. D., "Identification of Peripheral Cracks in Cylindrical Shells," ASME Paper No. 83-WA/DE-14, 1983.

67. Dentsoras, A. J. and Dimarogonas, A. D., "Resonance Controlled Fatigue Crack Propagation in Cylindrical Shafts Under Combined Loading," ASME Paper No. 83-WA/DE-26, 1983.

68. Chamis, C., Sinclair, J. H. and Lark, R. F., "Dynamic Response of Damaged Angleplied Fiber Composites," Modern Developments in Composite Materials and Structures, ASME, 1979, pp. 31-51.

69. Tracy, J. J., Dimas, D. J. and Pardeon, G. C., "Advanced Composite Damage Detection Using Modal Analysis Techniques," Proceedings of the Second Modal Analysis Conference, 1984, pp. 665-670.

70. Crema, L. B., Castellani, A. and Peroni, I., "Modal Tests on Composite Material Structures: Application in Damage Detection," Proceedings of the Third Modal Analysis Conference, 1985, pp.708-713.

71. Tsai, T., Yang, J. C. S. and Chen, R. Z., "Detection of Damages in Structures by the Cross Random Decrement Method," Proceedings of the Third International Modal Analysis Conference, 1985, pp. 691-700.

72. Akgun, M., Ju, F. D. and Paez, T. L., "Transmissibility as a Means to Diagnose Damage in Structures," Proceedings of the Third International Modal Analysis Conference, 1985, pp. 701-707.

73. "Modal Analysis Methods Applied to Structural Integrity Monitoring," Structural Dynamics Research Corporation, June 1985.

74. West, Walter, Fault Detection in Orbiter OV-101 Structure Related Structural Test Specimen, Loads and Sturctural Dynamics Branch Report, NASA/Johnson Space Center, September 1984.

75. West, Walter, "Single Point Random Modal Test Technology Application to Failure Detection," Shock and Vibration Bulletin, No. 52, Part 4, 1982, pp. 25-31.

76. West, Walter, "Illustration of the Use of Modal Assurance Criterion to Detect Structural Changes in an Orbiter Test Specimen," Proceedings of the Fourth International Modal Analysis Conference, 1986, pp. 1-6.

77. Haisty, B. S., West, W. and Mitchell, C., "Damage Detection in the Space Shuttle Orbiter Body Flap Test Specimen Using the Modal Assurance Criterion," Proceedings of the Advanced Composites Conference, 1985.

78. Yao, J. T. P., Toussi, S. and Sozen, M. A., "Damage Assessment From Dynamic Response Measurements," Proceedings of the Ninth United States National Congress of Applied Mechanics, 1982, pp. 315-322.

79. Yao, J. T. P., "Probabalistic Methods for the Evaluation of Seismic Damage in Existing Structures," Soil Dynamics and Earthquake Engineering, Vol. 1, No. 3, 1982.

80. Stephens, J. E. and Yao, J. T. P., "Survey of Available Structural Response Data for Damage Assessment," University of California Paper No. CE-STR-83-23, March 1984.

81. Adams, R. D. and Coppendale, J., "Measurement of the Elastic Moduli of Structural Adhesives by a Resonant Bar Technique," Journal of Mechanical Engineering Science, Vol. 18, No. 3, 1976, pp. 149-158.

82. Cempel, C., "Diagnostically Oriented Measures of Vibroacoustical Processes," Journal of Sound and Vibration, Vol. 73, No. 4, 1980, pp.547-561.

83. Cheng, J. S., Dunham, M. and Joanides, J., "Acoustic Test Response of the Space Shuttle Orbiter Body Flap," Proceedings of the Second International Modal Analysis Conference, 1984, pp. 635-637.

84. Griesbach, T. J. and Ayers, D. J., "Opening and Extension of Circumferential Cracks in a Pipe Subject to Dynamic Loads," Nuclear Engineering Design, Vol. 57, No. 1, April 1980, pp. 141-152.

85. Koester, D. L., "The Dynamic Behavior of Center Crack Tension Specimens During High Frequency Material Fatigue Tests," Proceedings of the Third International Modal Analysis Conference, 1985, pp. 794-801.

86. Mutch, Gordon F. and Russell, Richard, "Troubleshooting In-Plant Equipment Using Combined Test and Analysis," Proceedings of the First International Modal Analysis Conference, 1982, pp. 252-258.

87. Sproat, W. H. and Rowe, W. J., "Ensuring Aircraft Structural Integrity Through Nondestructive Evaluation," Lockheed-Georgia Company.

88. Verdonck, E. and Snoeys, R., "Life Time Prediction Based on the Combined Use of Finite Element and Modal Analysis Data," Proceedings of the Second International Modal Analysis Conference, 1984, pp.572-579.